AD_________________

Award Number: W81XWH-09-1-0498

TITLE: Measuring Blast – Related Intracranial Pressure Within the Human Head

PRINCIPAL INVESTIGATOR: Dr. Cynthia Bir

CONTRACTING ORGANIZATION:
Wayne State University
Detroit, MI 48202

REPORT DATE: August 2010

TYPE OF REPORT: Annual

PREPARED FOR: U.S. Army Medical Research and Materiel Command
Fort Detrick, Maryland 21702-5012

DISTRIBUTION STATEMENT:

Approved for public release; distribution unlimited

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*
31-08-2010

2. REPORT TYPE
Annual

3. DATES COVERED *(From - To)*
1 AUG 2009 - 31 JUL 2010

4. TITLE AND SUBTITLE
Measuring Blast-Related Intracranial Pressure Within the Human Head

5a. CONTRACT NUMBER

5b. GRANT NUMBER
W81XWH-09-1-0498

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Bir, Cynthia
VandeVord, Pamela
Leonardi, Alessandra

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Wayne State University

Detroit, MI 48202

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
U.S. Army Medical Research and
Material Command
Fort Detrick, Maryland, 21702-

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION / AVAILABILITY STATEMENT

Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT
The goal of this research effort is to determine the transient responses of the skull-brain system during exposure to blast to help identify the primary mechanism of blast-TBI. The aims of this proposal are (1) to ascertain the relationship between magnitude levels of incident pressure and values of intracranial pressure, surface strain, and kinematic response, (2) to investigate the effects of orientation on all three parameters, and (3) to compare pressure distribution patterns with a finite element model. Preliminary data indicate there are significant factors of paramount importance when performing ICP-PMHS testing: sensor location in the brain, exposure at blast, orientation of head and magnitude of the blast. Work in the remaining six months will consist of final PMHS testing and finite element modeling.

15. SUBJECT TERMS
Cadaver, blast neurotrauma, intra-cranial pressure

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			USAMRMC
U	U	U	UU	19	**19b. TELEPHONE NUMBER** *(include area code)*

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. Z39.18

Table of Contents

INTRODUCTION

The goal of this research effort is to determine the transient responses of the skull-brain system during exposure to blast to help identify the primary mechanism of blast-TBI. The aims of this proposal are (1) to ascertain the relationship between magnitude levels of incident pressure and values of intracranial pressure, surface strain, and kinematic response, (2) to investigate the effects of orientation on all three parameters, and (3) to compare pressure distribution patterns with a finite element model. The proposed research is *significant* because resolution of the mode of energy transfer and of the induced stresses within the skull-brain system will allow for creations of mitigation/protective techniques/equipment, as well as design of experiments investigating live-cell response using more reliable computer simulated models.

BODY

Since the grant was awarded in August 2009, we have undergone several key experiments in order to accomplish our specific aims. First, we determined linear acceleration values produced at the proposed blast overpressures using an instrumented biomechanical surrogate; the Hybrid III 50^{th} percentile head form. Secondly, we began optimization of specimen preparation and testing procedures to most accurately measure ICP during blast testing. We found that sealing techniques for placement of the ICP sensors in the human skull had to be modified from techniques previously used for animal testing. Third, we began measuring strains from multiple sites of the human skull during blast testing. We found that the techniques for placement of the strain gages needed to be improved to guarantee a dependable adhesion of such gages for the entire duration of the experiment.

A detailed description of our methodology, results and challenges are presented below.

1.1 Wayne State University shock wave generator (WSU-SWG).

To simulate a free field blast wave in the laboratory, the Bioengineering Center at Wayne State University houses a shock wave generator (**Figure 1**) activated by compressed helium. A shock wave generator is a tube consisting of two separate chambers: the driver, where the pressured gas is inserted by means of compressor system, and the driven, where the shock wave propagates (Celander 1954). In the simplest shock tube operation, the driver is separated from the driven by a replaceable membrane. For any given material the membrane ruptures at a particular pressure that is directly proportional to its thickness and allows the generation of the shock wave into the driven. (Note: because the wave is produced by compressed gas bursting a membrane instead of an actual chemical explosion, we use the term blast simulation instead of blast and shock wave instead of blast wave.) The test section usually contains air at atmospheric pressure before the bursting of the diaphragm . If the diaphragm bursts ideally, a uniform shock front quickly develops and propagates down the test section.

The WSU SWG had been used previously to conduct testing using a rodent model. In an effort to accommodate the larger cephalic specimens, an expansion section was built. This expansion section was carefully design to create the ideal wave profile without refractions. It measures 30 inches and diameter and can accommodate the specimens to be placed in the primary blast wave with adequate air flow around all sides.

The incident shock wave overpressure values achieved were approximately 13.5, 16.3, 20.3 and 22.3 psi (93, 112, 140, and 154 kPa) in magnitude. These pressure values were measured by a probe placed at the site where the specimen was to be positioned approximately 49 inches from the open end of the tube. The probe contains pressure gages that measure the static and stagnation pressures; stagnation pressure, also called incident pressure, consists of static and dynamic pressure combined and subsequent data processing allows calculation of dynamic pressures.

Calibration of the WSU SWG determined that the generated pressure waveforms have a decaying profile credibly similar to that of free field blast (**Figure 2**). However, it is very important to note that not all zones within the shock tube are appropriate for blast simulation: at some locations within the tube, the effects of anomalous flow features are exaggerated and will corrupt the experimental conditions. Hybrid III and human specimen were consistently placed at 49 inches from the open end of the tube, where conditions were deemed optimal for free field blast simulation based on wave diagram studies conducted.

Figure 1: Wayne State University shock wave generator. This shock tube is housed at the Bioengineering Center. It is approximately 26 feet long and 30 inches in diameter at the open end. At the opposite end is the driver, which is 30 inches long and 12 inches in diameter.

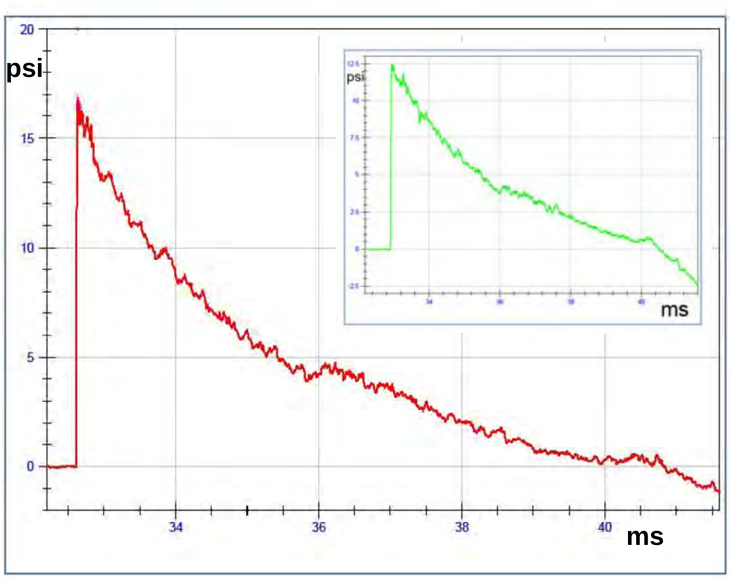


Figure 2: Stagnation pressure profile collected near the location where samples are placed for testing. In this example the peak stagnation pressure was around 17 psi (117 kPa) and the positive phase duration was 8 ms.
<u>Insert</u>: Corresponding static pressure profile for the same test. Peak static pressure was around 12.5 psi (86kPa) and the positive phase duration was around 7.5 ms.
The dynamic pressure profile is calculated from such profiles.

1.2 Pressure sensors

Commercially available sensors from Endevco (models 8515C and 8530C), FISO Technologies (FOP-MIV model) and PCB Piezotronics (102A 06 model), were used at the specimen site and along the tube to record the incident shock wave overpressure and the intracranial pressure (ICP) respectively (**Figure 3**). The sensors differ on several levels according to their purpose. First, the mechanism of measuring pressure is distinctive: sensors used to measure air over-pressure utilize either a piezoresistive or a quartz piezoelectric element to detect sudden change in ambient pressure. They are rugged and able to survive many blast test situations, although they possess high sensitivity and reliability. The monitoring of the ambient overpressure at the target was provided by a pressure probe that contained two Endevco sensors placed frontally and side on with respect to the shock front.

Sensors used to assess ICP utilize optic technology, measuring pressure by converting wavelength-modulated light into a voltage value. They were designed for medical applications; therefore the sensor is very fragile and weighs only 0.163mg. The tip of the sensor, excluding the connecting optic fiber, measures approximately 0.5mm both in diameter and in length. These characteristics of the sensors are especially important when working in the brain since the sensor should approximate the density of the tissue surrounding it to create as little disturbance as possible. Otherwise, inertia of the sensor may affect the reading of in vivo pressure as intended.

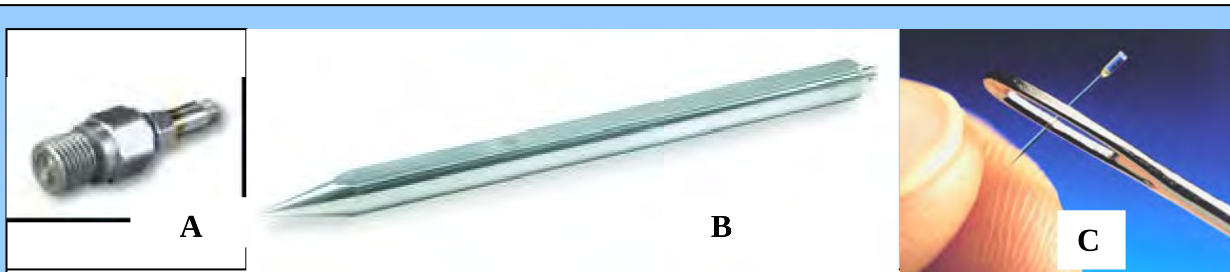


Figure 3: Examples of pressure sensors used for shock tests. (A) PCB Piezotronics pressure sensor measuring the static component of the shock wave in air along the tube; (B) pressure sensor using Endevco sensor to measure static and stagnation pressures next to the specimen; (C) FISO Technologies optic pressure sensor for intracranial measurements.

1.3 Sample preparation

Preliminary testing has been conducted to assess several key factors and provide future directions. For determining linear acceleration values produced at the proposed blast overpressures, we used an instrumented Hybrid III 50th percentile head form. A tri-axial block of linear accelerometers was placed at the center of gravity of the headform. Data was collected using a TDAS system (DTS, Inc) at 150 kHz.

For determining ICP values and strains, we employed a non-embalmed PMHS head without a neck, which had been frozen. Three FISO optic sensors were implanted in the right frontal

cortex, right lateral ventricle, and right parietal lobe and the respective depths of the tip of the sensors from the outer surface of the skull were 25mm, 65mm, and 30mm. Holes were made in the skull using a Dremel rotary tool; each hole (d=1.2mm) had at least three supporting screws that helped hold the sensor in place once inserted (**Figure 4A**). The FISO sensors were anchored to the skull by using bone cement that adhered to the skull and the screws reinforcing the anchoring site and providing sealing of the hole (**Figure 4B**).

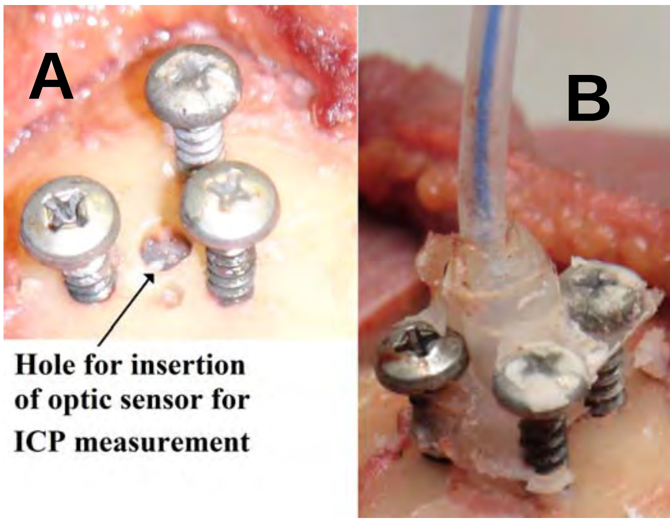


Figure 4: Placement of the FISO optic sensor on the skull of the PMHS.
(A) Hole for insertion of optic sensor with supporting screws already in place.
(B) Optic fiber (blue) protected by plastic sheaving, anchored to screws by bone cement. In this picture the cement was partially removed to show the screws underneath. In the actual setup cement is poured in a form that completely encloses the screws and it is left to cure for several minutes. The sheaving on the exposed fiber protects from the blast wind and it is not present on the tract that goes into the brain.

To measure strain, five rosettes were glue to the skull on the left zygomatic bone, the left sphenoid bone, the left parietal bone and the left side of the frontal and occipital bones (20mm on the left side of the midline). The glue adopted was a two part compound: one part was placed on the surface of the skull after a meticulous cleaning and drying process; the second part was placed on the rosette. Once the two parts were pressed together a chemical bond was formed that provided great adhesion. A sealant was also applied on the rosette's exposed surface to avoid contact with bodily fluids that would have altered strain results.

Note that all three pressure sensors were mounted on the right side of the brain, while the five rosettes strain gages were placed on the left side of the skull; this setup was chosen to collect homogeneous data among different locations see next section.

1.4 Experimental setup

The Hybrid III head form was placed in the tube under two boundary conditions. First it was tested with a Hybrid III neck. An interface plate rigidly mounted the head and neck to the bottom of the expansion tube in the same position along the length of the tub where the PHMS specimens will be placed (**Figure 5A**). Next the Hybrid head form was mounted without the neck in a soft net that was suspended in the same manner as the PMHS specimens would be during testing (**Figure 5B**); this was the second boundary condition. For each boundary condition the Hybrid III head form was exposed to several incident shock wave overpressures (target values were 14.5, 17, 20 and 22 psi, which is respectively 100, 117, 138, and 152 kPa); to check for repeatability of results there were at least three tests for each pressure magnitude.

Monitoring of the overpressures delivered to the dummies was provided by a pressure probe placed next to the samples.

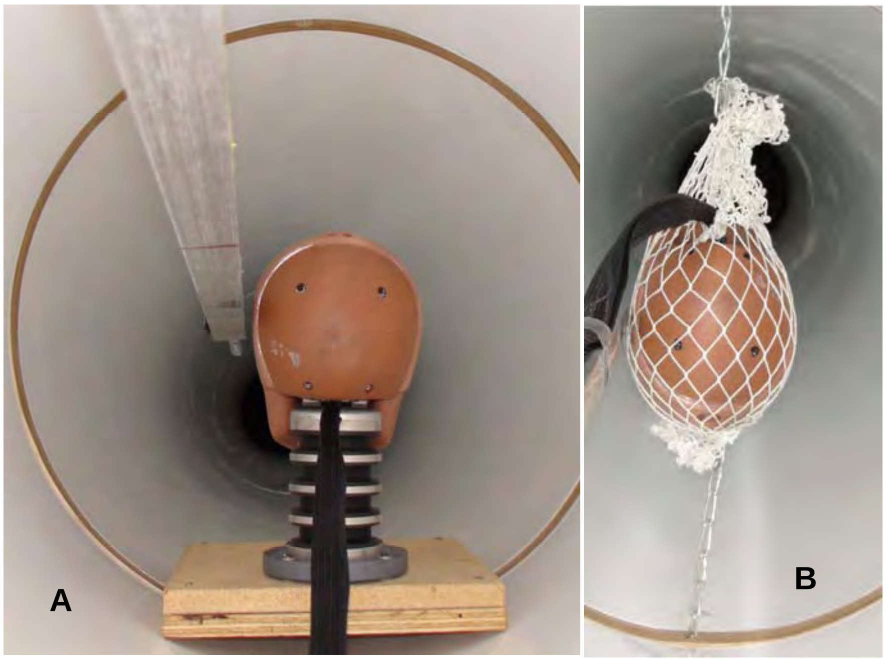


Figure 5: Placement of the Hybrid III head form under two different boundary conditions.
(A) H-III head and neck rigidly mounted on a platform at 49 inches from the open end of the tube.
(B) H-III head inside a soft net suspended at 49 inches from the end of the tube at the location where PMHS specimens will be placed for testing.
The pole next to the dummy in both pictures contains the pressure sensors that plot the static and dynamic over-pressures occurring during testing.

For the PMHS testing, the specimen was mounted upside down in a soft net that was suspended in the center of the tube-section at 49 inches from the open end as shown in **Figure 5B** for the head form. Three target overpressure exposures were chosen: 14.5, 17, and 22 psi. For each target overpressure, a set of five positions were investigated: shockwave hitting frontally (nose facing the blast); shockwave hitting the left side (strain gages facing the blast) ; shockwave hitting the back of the head; shockwave hitting the right side (pressure sensors facing the blast); then again shockwave hitting frontally (nose facing the blast). This last position was repeated at the end of each set to check for reproducibility of results. In fact, due to the harsh environment in which the sensors are required to work, we had to balance the need to maximize the number of successful tests with the necessity to test that results were repeatable.

Results

2.1 Hybrid III testing for linear accelerations

We tested accelerations generated during blast simulation with an instrumented Hybrid III 50^{th} percentile head form. These tests were conducted to eliminate the need for extraneous instrumentation of the PMHS. The results from this testing indicates that it would be unnecessary to add the instrumentation to the cephalic specimen. Attaching a block of accelerometers and angular rate sensors to the skull would affect strain and/or pressure measurements in the PMHS due to fixation techniques and added mass and rigidity.

The accelerometers were filtered using a CFC1000 filter (-3dB point = 1650 Hz) as described by SAE J211. The acceleration data at the center of gravity (CG) was evaluated using Head Injury Criterion (HIC). The resultant of the 3 accelerometers at the CG was calculated and the HIC calculations computed from this resultant. All acceleration data processing was conducted using Diadem 11.1 (National Instruments). HIC values are provided in **Table 1**. Also included in this table is the percent risk for MTBI. These values are calculated from a logistic regression curve created by Zhang et al. (2004). These values are below 10%, which indicates that the conditions studied in our blast overpressure system do not induce injurious linear accelerations.

Filename	HIC15	% Risk of MTBI	Target Overpressure
ExpansionTubeTest1	14.84	7.1470	17 psi
ExpansionTubeTest2	19.91	7.5402	17 psi
ExpansionTubeTest3	18.71	7.4454	17 psi
ExpansionTubeTest4	20.17	7.5609	17 psi
ExpansionTubeTest5	21.67	7.6813	17psi
ExpansionTubeTest6	26.8	8.1064	17psi
ExpansionTubeTest7	12.79	6.9935	14.5 psi
ExpansionTubeTest8	11.4	6.8911	14.5 psi
ExpansionTubeTest9	23.46	7.8272	17 psi
ExpansionTubeTest10	9.61	6.7613	14.5 psi
ExpansionTubeTest11	10.26	6.8082	14.5 psi
ExpansionBlastTest12	19.98	7.5458	17 psi
ExpansionBlastTest13	10.7	6.8401	17 psi
ExpansionBlastTest14	9.78	6.7735	17 psi
ExpansionBlastTest15	7.39	6.6035	14.5 psi
ExpansionBlastTest16	9.11	6.7255	14.5 psi
ExpansionBlastTest17	8.71	6.6969	14.5 psi
ExpansionBlastTest18	14.38	7.1123	17 psi
ExpansionBlastTest19	19.17	7.4816	20 psi
ExpansionBlastTest20	32.98	8.6469	20 psi
ExpansionTubeTest21	23.82	7.8569	20 psi
ExpansionBlastTest22	26.62	8.0911	22 psi
ExpansionBlastTest23	31.69	8.5315	22 psi
ExpasionTubeTest24	29.41	8.3308	22 psi

Table 1: Linear acceleration data from Hybrid III tests

In combination with the gathering of acceleration data, we collected data regarding the speed of the shock front and the incident and static overpressure values at the specimen's location in 27 tests. **Table 2** shows the average speed of the shock front, the average incident overpressure (named **AOP** for Ambient Over-Pressure), and the average static overpressure for each target pressure. **Table 3** shows the incident and static overpressures for each test. Note the consistency of pressure values provided by the WSU-SWG for each of the target pressures.

TARGET PRESSURE	AVG PEAK AOP PSI (kPa)	AVG FRONT SPEED m/s	AVG PEAK STATIC OP PSI (kPa)
14.5 PSI	13.5 PSI (93kPa)	444.6	10.6 (73.1)
17 PSI	16.3 PSI (112kPa)	459.8	12.6 (86.9)
20 PSI	20.3 PSI (140kPa)	481.7	15.7 (108.3)
22 PSI	22.3 PSI (154kPa)	490.0	15.8 (108.9)

Table 2: Averages for collected data: shock front speed, peak ambient overpressure (AOP), and peak static overpressure.

PEAK A.O.P. psi	PEAK STATIC O.P. psi	TARGET A.O.P.		PEAK A.O.P. psi	PEAK STATIC O.P. psi	TARGET A.O.P.
15.35	10.83	14.5 psi		16.65	12.52	17 psi
13.69	10.72	14.5 psi		16.21	12.31	17 psi
14.12	10.93	14.5 psi		15.83	11.79	17 psi
13.92	10.07	14.5 psi		16.86	12.35	17 psi
12.55	9.79	14.5 psi		16.72	12.69	17 psi
11.96	9.45	14.5 psi		16.38	12.32	17 psi
12.04	9.39	14.5 psi		16.12	12.04	17 psi
12.7	11.18	14.5 psi		15.97	12.93	17 psi
13.85	11.49	14.5 psi		15.9	13	17 psi
14.47	12.34	14.5 psi		16.41	14.37	17 psi
20.43	15.38	20 psi		21.81	15.57	22 psi
20.31	15.66	20 psi		23.12	15.76	22 psi
20.3	16.09	20 psi		22.85	17.27	22 psi
				21.56	14.42	22 psi

Table 3: Collected data: peak ambient overpressure (AOP), and peak static overpressure at the specimen's location for 27 tests at different magnitudes.

2.1 PMHS preliminary testing results with ICP sensors

During 18 blast simulations, we collected pressure data in three different parts of the brain of a PMHS specimen. **Table 4** presents the list of tests for each sensor. **Table 5** presents the maximum pressure values for each case. For both tables, note that the last two columns give information on the ambient overpressure of the simulated blast and the position of the side of the head that faces the shockfront (in parenthesis is the type of gage hit first for lateral hit).

frontal cortex sensor	ventricle sensor	parietal sensor	target pressure	hit facing side
yes	yes	NA	14.5 psi	front
yes	yes	NA	14.5 psi	front
yes	yes	NA	14.5 psi	left SG
yes	yes	NA	14.5 psi	back
yes	yes	NA	14.5 psi	right (Optic)
yes	yes	NA	14.5 psi	front
yes	yes	NA	17 psi	front
yes	yes	NA	17 psi	left (SG)
yes	yes	NA	17 psi	back
yes	yes	NA	17 psi	right (Optic)
yes	yes	NA	17 psi	front
yes	yes	NA	22 psi	front
yes	yes	NA	22 psi	left (SG)
yes	yes	NA	22 psi	back
broken	yes	NA	22 psi	right (Optic)
NA	yes	yes	22 psi	front
NA	yes	yes	17 psi	front
NA	yes	yes	14.5 psi	front

Table 4: List of simulated blast tests according to location in the brain, target magnitude and hit-facing side.

max frontal cortex ICP (psi)		max ventricle ICP (psi)		max parietal ICP (psi)	AVG AOP	hit facing side
14.44		11.39		NA	13.5 psi	front
14.15		9.83		NA	13.5 psi	front
13.22		10.25		NA	13.5 psi	left (SG)
(-14.24) 8.26		8.1		NA	13.5 psi	back
9.38		9.68		NA	13.5 psi	right (Optic)
19.79		12.36		NA	13.5 psi	Front
24.08		14.18		NA	16.3 psi	Front
18.53		12.66		NA	16.3 psi	left (SG)
(-11.51) 4.15		5.8		NA	16.3 psi	Back
11.41		10.05		NA	16.3 psi	right (Optic)
23.59		14.2		NA	16.3 psi	Front
25.88		17.34		NA	22.3 psi	Front
(-7.66) 8.67		14.5		NA	22.3 psi	left (SG)
(-25.72) 7.9		8.32		NA	22.3 psi	Back
13.79		14.82		NA	22.3 psi	right (Optic)
NA		16.39		28.09	22.3 psi	front
NA		13.57		16.85	16.3 psi	front
NA		11.27		14.09	13.5 psi	front

Table 5: Data collected during the 18 simulated blast tests according to brain location, average ambient overpressure and hit-facing side.

The tests labeled "front" are the beginning and end tests for that particular magnitude and they were utilized to check the repeatability of the setup. **Figure 6** shows an example of the comparison of pressure profiles at 20 psi target pressure for the frontal cortex and the ventricle location respectively: the red line is the beginning test and the green line is the end test in both diagrams. In all comparisons there was a good reproducibility of results.

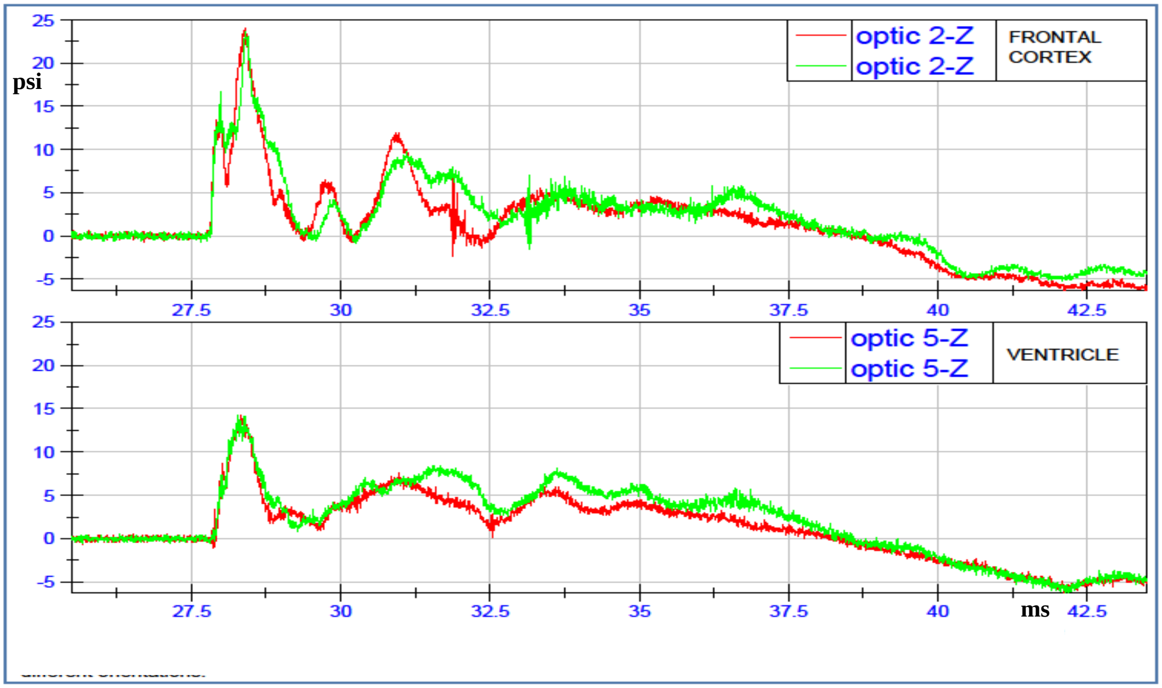


Figure 6: Example of the comparison of pressure profiles at the 20 psi target pressure for the frontal cortex and the ventricle location respectively: the red line is the beginning test and the green line is the end test in both diagrams. Reproducibility is very satisfactory.

In **Table 5** some negative numbers appear in parenthesis in the frontal cortex column. Such numbers represent a noticeable decrease in IC pressure that happened before the IC pressure started to increase. This behavior is very noticeable in all the "Back" cases, but of all the lateral hits, test 13 is the only one that stands out. It is likely that the head was partially out of position before the shock wave hit, explaining the behavior more similar to the "back" tests.

Figure 7 shows the IC pressure profiles created by shockwaves during "back" hits in the frontal cortex at different magnitudes and **Figure 8** shows the IC pressure profiles in the frontal cortex created by the left side hits. As anticipated, observe that the left side exposure has an anomalous behavior at 22 psi AOP. **Figure 9** presents the ICP profiles in the frontal cortex due to right side exposure. A little reduction of IC pressure (dip) before beginning of pressurization is visible in all three diagrams. These dips could represent a clue to the mechanism by which the overpressure is transmitted inside the brain. We believe (Dal Cengio Leonardi et al. 2009) that there is a mode of skull deformation due to a global compression of the skull. According to the thickness of the skull, what side of the head is facing the shock front, and the irregular geometry of the skull, deformation would create different patterns (profile shape) of pressure readings in relation to sensor location in the brain and to the forms of exposure. Due to geometry and specific material responses of the skull and its interfaces, some areas inside the brain could

actually see a release of pressure prior to global com pression. These preliminary studies already show the presence of patterns in the IC pressure profiles as it can be noted in most of the figures presented below.

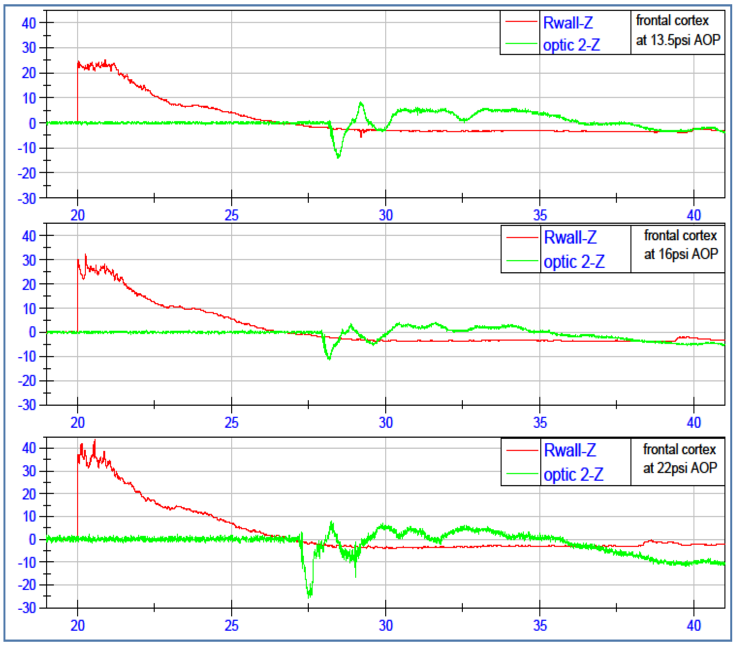


Figure 7: IC pressure profiles (green) in the frontal cortex during a BACK exposure. Three magnitudes of shockwave were tested. All diagrams use the same scale and units: in the Y-axis (psi) and in the X-axis (ms). The red profile is the pressure profile at the trigger station, which sees the shockwave passing by a few milliseconds before the specimen, as it is about 13 feet upstream from it. At the trigger location the ambient overpressure recorded is higher than the AOP at the specimen because of the conical shape of the tube.
Note that the IC pressure goes below ambient (called dip) before beginning pressurization. This behavior is consistent at all exposures and the dip increases with the magnitude of the shockwave.

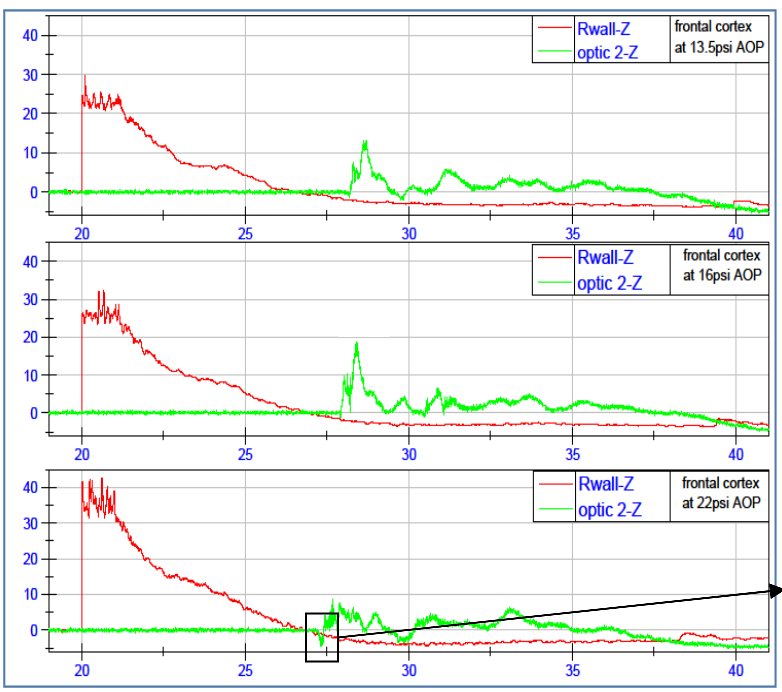
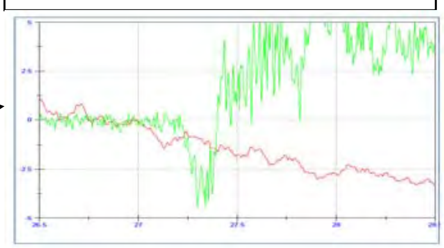


Figure 8: IC pressure profiles (green) for the frontal cortex during LEFT-SIDE exposures to blast (see also legend in previous figure). Three shock-wave magnitudes tested.
<u>Insert:</u> at magnitude of 22 psi the IC pressure in the frontal cortex sees a reduction in pressure prior to initiation of pressurization.
Note in the diagrams that this behavior is anomalous for this head position as compared to previous magnitudes.



In **Figure 9** the bottom diagram documents failure of th e frontal cortex sensor at 22 psi AOP around the 29th ms.

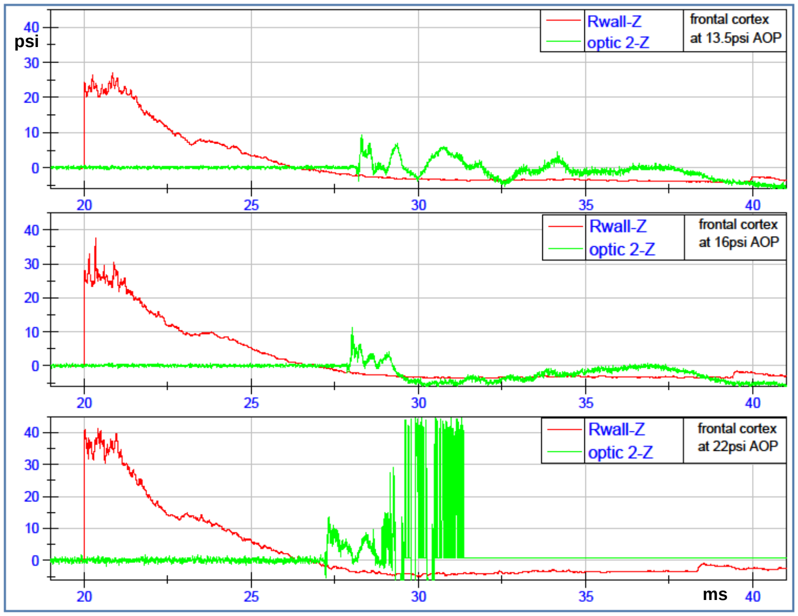


Figure 9: IC pressure profiles (green) in the frontal cortex during a RIGHT-SIDE exposure. Three shockwave magnitudes tested. All diagrams use the same scale and units: in the Y-axis (psi) and in the X-axis (ms). The red profile is the pressure profile at the trigger station.
Note the little dip in each diagram before beginning of pressurization. This behavior is consistent at all pressure magnitudes.
The bottom diagram shows failure of the sensor during the test at 22 psi AOP for RIGHT-SIDE exposure.

Figure 10 presents the pressure results in the frontal cortex for frontal exposure. Notice that the peak pressure values reached in the frontal cortex increase with increased AOPs, and also they are consistently above the average peak AOP values delivered (see Tables 4 and 5).

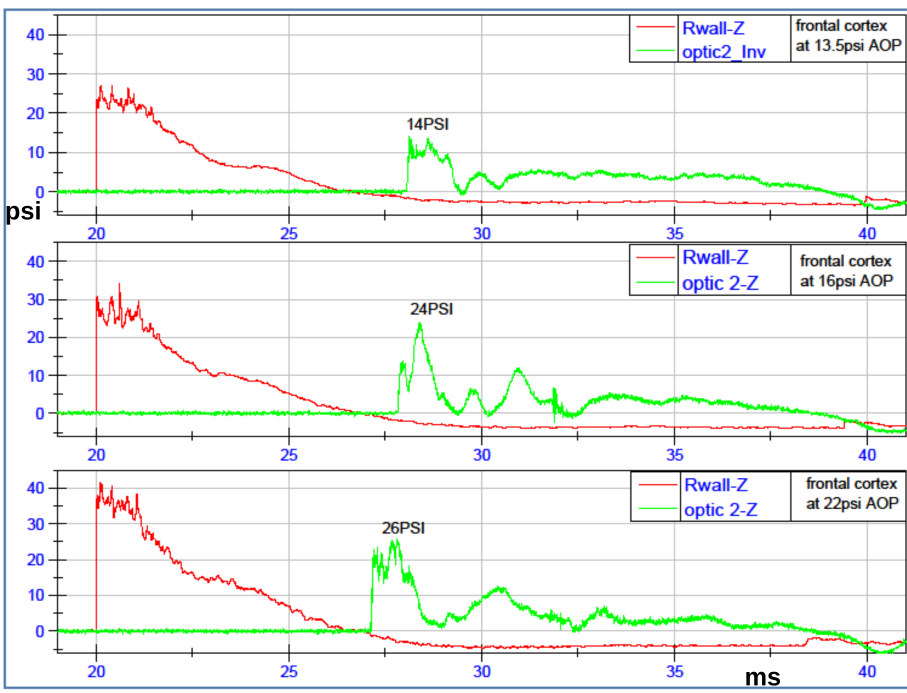


Figure 10: IC pressure profiles (green) in the frontal cortex during a FRONT exposure. Three magnitudes tested. All diagrams use the same scale and units. The red profile is the pressure profile at the trigger station.
The approximate peak IC pressure for each test was added to the diagram and the average peak AOP is on the top right corner. ICP peak values were consistently higher than respective AOP for this exposure and sensor location.

Figure 11A, 11B, 11C, and 11D illustrate the ICP results in the ventricle for front, back, right-side, and left-side exposure at the three chosen AOP magnitudes. The pressure profiles recorded in the ventricle are definitely more uniform than for the frontal cortex placement. This can probably be attributed mostly to the location: the deeper the sensor is in the brain, the less it may

be affected by “surface” differences, and the more it would instead see a global com pression effect.

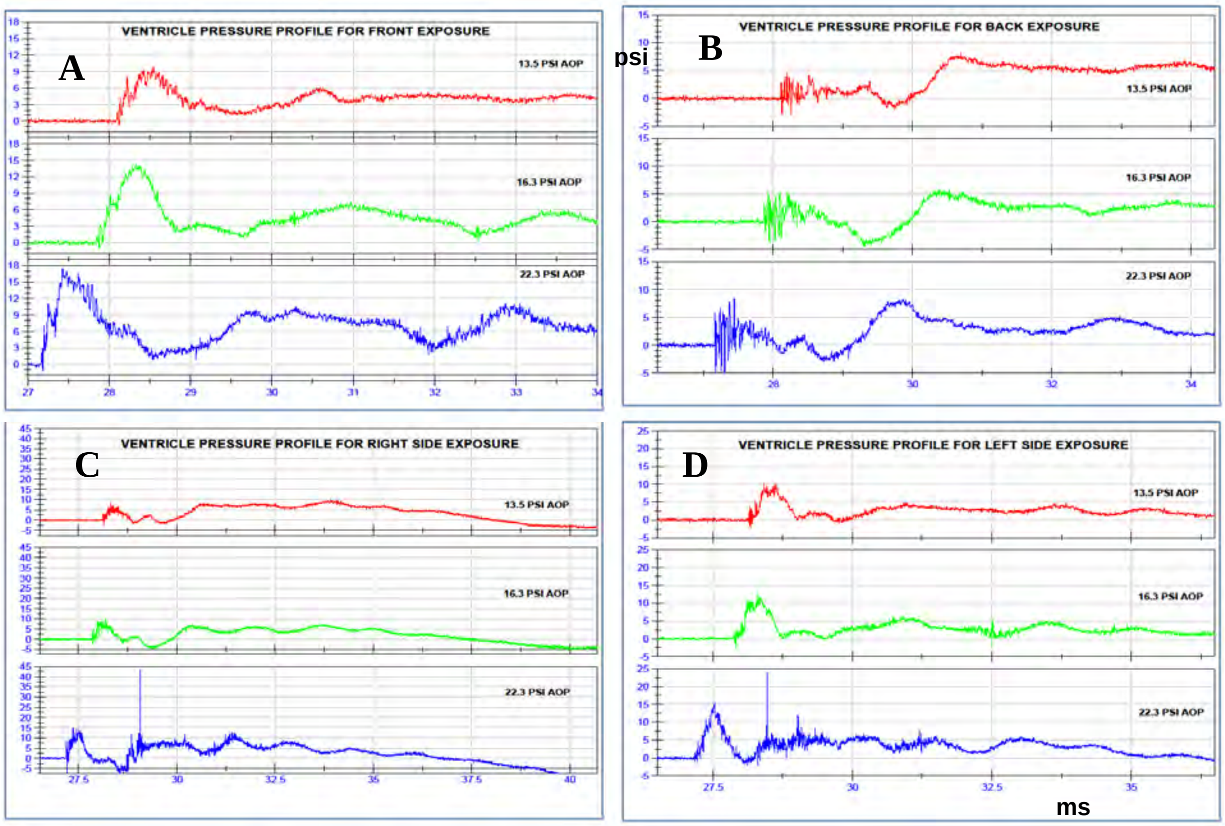


Figure 11: IC pressure profiles recorded in the ventricle are definitely very similar despite the exposure is different. Diagrams use the same units but not the same scale. Exposures: A) Front; B) Back; C) Right side; D) Left Side.

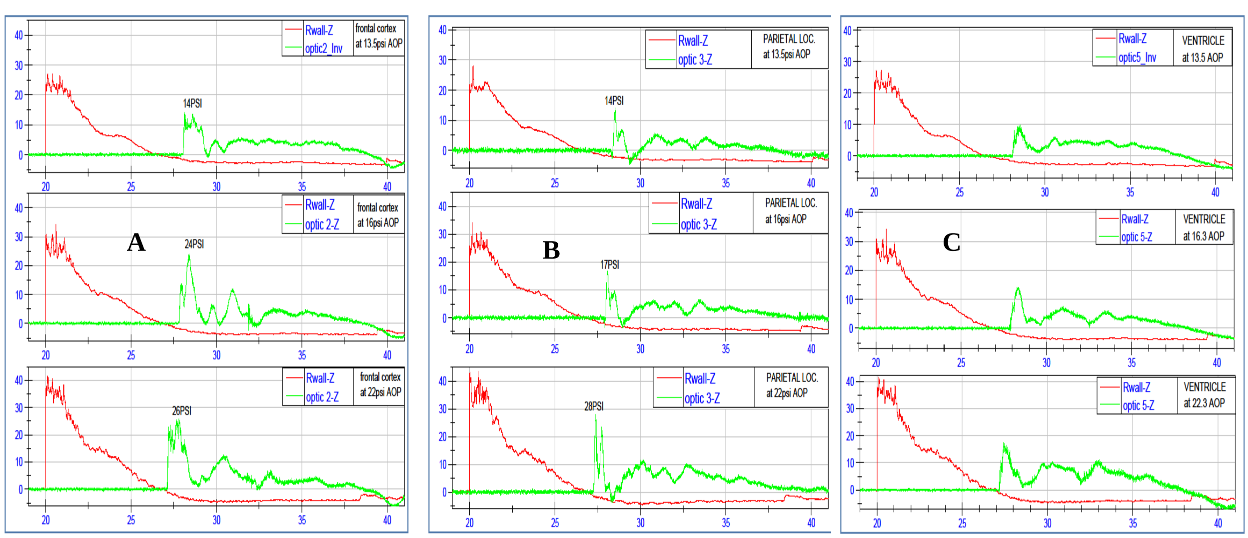


Figure 12: IC pressure profiles of different locations in the brain at the same Front exposure. A) Frontal cortex; B) Parietal lobe; C) Ventricle.

Figure 12A, 12B, and 12C compare sensor location for the same exposure. The diagrams clearly show consistency of the pressure profile shapes for the same brain location even at different AOPs; however each location has a unique signature.

Finally as mentioned already for some of the figures presented, there seem to be a correlation between AOP magnitude and ICP peak value: higher AOPs usually increase the ICP peak values in each exposure, for any sensor placement.

3.1 PMHS preliminary testing results with strain gages

During 18 blast simulations, we collected strain data in five regions of the skull of a PMHS specimen: left zygomatic bone, the left sphenoid bone , the left parietal bone and the left frontal and occipital bones (20 mm from midline). **Table 6** presents a summary of preliminary strains data for each test and region.

	Frontal	**Occipital**	**Parietal**	**Zygomatic**	**Sphenoid**
Test	Strain (us)	Strain (us)	Strain (us)	Strain (us)	Strain (us)
1	3869	249	4125	1482	1275
2	674	263	4772	265	3690
3	490	214	2573	3167	No Data
4	223	313	1348	No Data	No Data
5	337	851	3916	No Data	No Data
6	1677	548	4258	No Data	No Data
7	3580	1181	1923	No Data	No Data
8	3152	1323	2819	No Data	No Data
9	2487	652	839	No Data	No Data
10	1678	1022	1570	No Data	No Data
11	3024	829	2359	No Data	No Data
12	3082	1848	No Data	No Data	No Data
13	2919	1333	No Data	No Data	No Data
14	681	297.5	No Data	No Data	No Data
15	1593	642	No Data	No Data	No Data
16	2557	176	No Data	No Data	No Data
17	2961	468	No Data	No Data	No Data
18	1637	535	No Data	No Data	No Data

Table 6: Strain data collected during the 18 simulated blast tests according to location,

The severity of the tests resulted in the loss of three of the five strain gages during the duration of the test series. Further data analy sis is necessary to determine the applicability of this data to a math model.

Discussion

There is a p ressing need for a com prehensive explanation of the mechanism of traumatic brain injury after exposure to blast, and the testing of instrum ented PMHS specim ens will becom e increasingly important. Historically, some animal tests have been designed and carried out in an attempt to learn m ore about the m echanism of shock wave transmission to the brain, but only a few animal studies recorded direct pressu re within the b rain tissue during exposure to blast (Chavko 2007; Clemedson 1956; Clemedson 1961a and b; Romba 1961; Saljo 2008; Dal Cengio Leonardi 2009). In fact such experim ents are challenging to setup because animal tests carry the burden of the com plex preparation of the animals in addition to the s trict guidelines for animal handling. It is of para mount importance to conduct tests in a way th at will maxim ize the attainment of dependable results and m inimize the sacrifice of anim als: by using PMHS specimens we combine these to the advantage of working with the human unique geometry.

We began optim izing specimen preparation and test ing procedures in orde r to m ost accurately measure ICP during blast testing. We found that sealing techniques for placem ent of the ICP sensors in the hum an skull had to be m odified from techniques previously used for anim al testing. The hum an skull is thicker and harder th an rodent skull; therefore screw s used for anchoring the pressure sensor during anim al testing proved to be too s mall to be em ployed. Eventually self-tapping screws were found that served the purpose, but we started a collaboration with the N eurosurgery Department at W ayne State University and we expect m ajor tool improvements for the next PMHS testing.

During specimen preparation there were a few challenges that we were not able to overcome:

- The delivered specimen did not have the requi red neck length (it was cut at C3, cervical vertebrae, instead that at T1, thoracic verteb rae). The neck length is req uired to expose proper tissue segments from the left and right common carotid arteries, internal jugular veins, and the spinal dura mater. Such segments are to be connected to a perfusion system to pressurize the head before testing and assu re IC conditions as clos e to an alive subject as possible. This procedure was not performed for this first study.
- The specimen was previously frozen. Veins a nd arteries are not we ll preserved in a frozen environment unless prep ared prior to freezing. This condition also affected the ability to connect the segments to the perfusion system.

New PMHS specim en will have the requir ed neck length and possibly will be “fresh”, not previously frozen, and we expect to a have a perfusion system in place for the next PMHS test.

Keeping the integrity of pressure sensors and strain gages during testing was a difficult challenge because of the harsh en vironment. Only two sens ors survived the du ration of the test series ; therefore the strain data are incomplete. In f uture tests, the placement of the gag es will be verified to ensure proper attachment is not an issue. Also, additional strain relief will be added to the sensor wires both at the sensor attachment point and at various locations along the wire. This

will be especially critical where the sensor wires pass through the netting: it is an inherently problematic location for wires to be damaged. During testing there were also a few problems with the pressure sensors: the sensor placed in the frontal cortex failed during a test; and cable issues prevented collection of most of the data from the sensor placed in the parietal lobe. However sensor breakage was lower than expected for a first setup: the expertise used to protect the optic sensors proved to be quite successful and ICP findings were very consistent.

Our results showed that reproducibility of pressure profiles was good when comparing the beginning and end test for each magnitude; this justifies the adoption of the set of five positions (as explained in section 1.4) for all future testing. Our results also showed a correlation between AOP magnitude and ICP values: higher AOPs usually increased the ICP peak values in each exposure, for any sensor placement. Finally these preliminary studies suggested the presence of patterns connected to sensor location in the IC pressure profiles, as it can be noted in all the figures presented that had diagrams with same exposure and sensor location at the three chosen AOP magnitudes. We hypothesize (Dal Cengio Leonardi et al. 2009) that there is a mode of skull deformation due to a global compression of the skull. According to the thickness of the skull, what side of the head is facing the shock front, and the irregular geometry of the skull, deformation would create different patterns of pressure readings in relation to sensor location in the brain and to the forms of exposure. Additional investigations will be carried on to fully examine this hypothesis.

KEY RESEARCH ACCOMPLISHMENTS

- Optimization of specimen preparation, instrumentation and testing procedures
- Determination that pressure sensor location has a major role in pressure measurements
- Incorporation of neurosurgical techniques into methodologies

REPORTABLE OUTCOMES

DM102839 - "Determination of Skull/Brain Frequency Response to Shock Wave Loading" was submitted to extend this work. It was chosen as an alternate. If funded, the current work will serve as the guideline for all future work proposed in DM102839.

CONCLUSION

In conclusion, we demonstrated that there are significant factors of paramount importance when performing ICP-PMHS testing: sensor location in the brain, exposure at blast, orientation of head and magnitude of the blast. Work in the remaining six months will consist of final PMHS testing and finite element modeling.

REFERENCES

Celander HC, CJ. 1954. The use of a compressed air operated shock tube for physiological blast research. Acta Physiologica Scandinavica 33(1):6-13.

Chavko M. 2007. Measurement of blast wave by a miniature fiber optic pressure transducer in the rat brain. Journal of Neuroscience Methods 159(2):277-281.

Clemedson CJ. 1956. Shockwave transmission to the central nervous system. Acta Physiologica Scandinavica 37(2-3):204-214.

Clemedson CJ, A. 1961a. Transmission of elastic disturbances caused by air shock waves in a living body. Journal of Applied Physiology 16(3):426-430.

Clemedson CJ, Jonsson, A. 1961b. Transmission and reflection of high explosive shock waves in bone. Acta Physiologica Scandinavica 51:47-61.

Dal Cengio Leonardi A, Bir CA, Ritzel DV, Vande Vord PJ (2009). The e ffects of intracranial pressure sensor location and skull aperture s during exposure of a rat model to an air shock wave. The Second Joint Symposium of the International and National Neurotrauma Societies, Santa Barbara, CA, Poster Presentation, September 2009.

Romba JJM, Paul. 1961. The propagation of air shock waves on a biophysical model. In: Laboratories UAOHE, editor. Aberdeen Proving Ground, Maryland: Armed Services Technical Information Agency. p 1-25.

Saljo A, Arrhen F, Bolouri H, Mayorga M, Hamberger A (2008). Neur opathology and pressure in the pig brain resu lting from low-impulse nois e exposure. Journal of Neurotraum a 25: 1397-1406.

Zhang L, Yang, KH, King, AI (2004). A proposed injury threshold for mild traumatic brain injury, J Biomechanics 126 (2): 226-36.